Understanding Ultrafine Particles Indoors

http://www.crln.org/files/images/candle_flame_0.jpg

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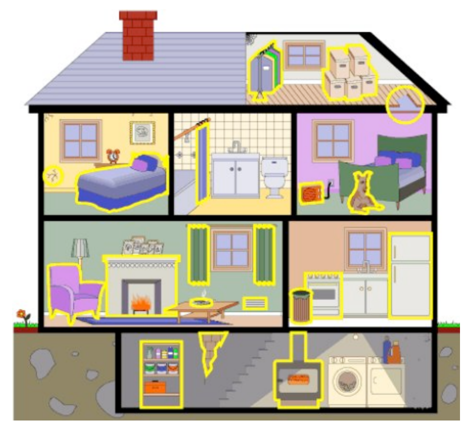
http://static.howstuffworks.com/gif/gas-vs-electric-cooking-1.jpg

http://yourtreasuredlegacy.com/images/elementary-classroom-2.jpg

http://blog.aarp.org/shaarpsession/traffic.jpg



http://www.coelhoconstruction.com/air_quality.htm

Acknowledgments and disclaimer

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- Disclaimer:
  - The statements and conclusions in this presentation are those of the researchers and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Ultrafine particles indoors: Background

- Emerging health concerns about UFP exposure
- New evidence about UFP in atmosphere
  - Regional nucleation events
  - Motor vehicles as prominent sources
- Independence of UFP from $PM_{2.5}$
- Most UFP exposure likely occurs indoors
- Little known about UFP levels indoors and influencing factors

Study objectives and goals

- Objectives: Advance knowledge regarding UFP levels and associated exposures in California classrooms and houses.
- Goals:
  - Characterize UFP levels in sample of houses & classrooms
  - Characterize factors that influence levels
  - Quantify exposure to household occupants and classroom students at sites monitored
  - Apportion exposures to major source categories

Study approach

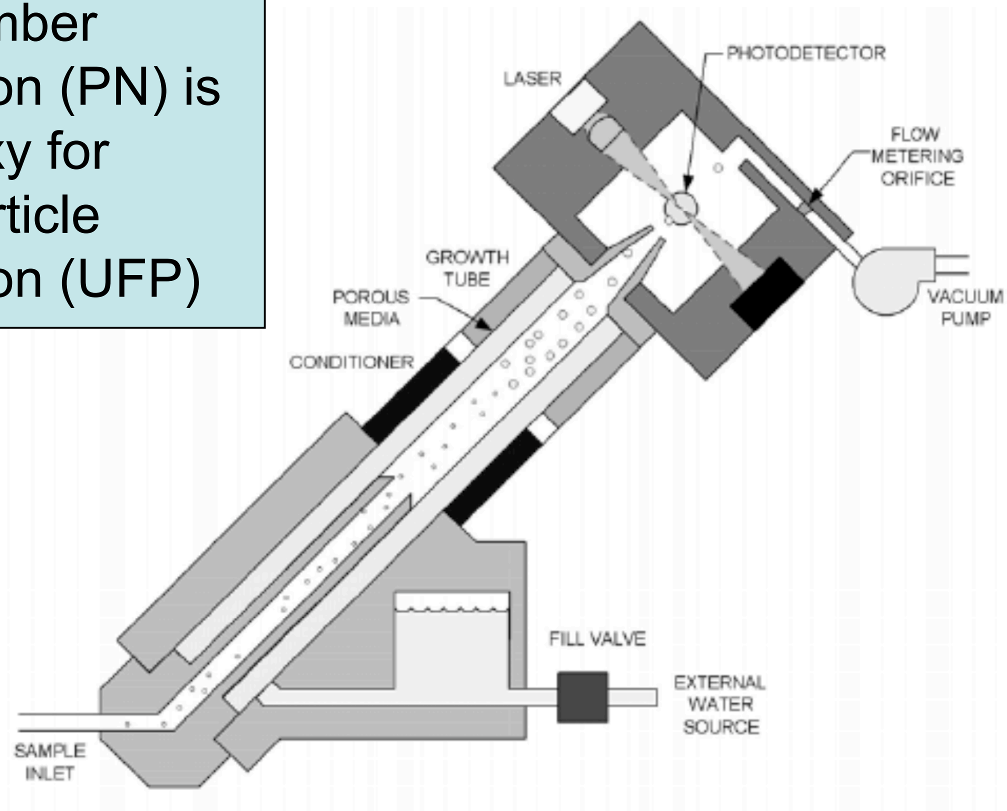
- Assemble instrumentation package
  - Real-time measurement of UFP and copollutants
  - Temperature & proximity sensors w/ data loggers
  - Occupant questionnaires and direct observation
- Conduct field monitoring campaign
  - 7 houses & 6 classrooms
  - Observational monitoring: ~ 3 days at each site
  - Manipulation experiments at each site
- Conduct extensive interpretive analysis of data

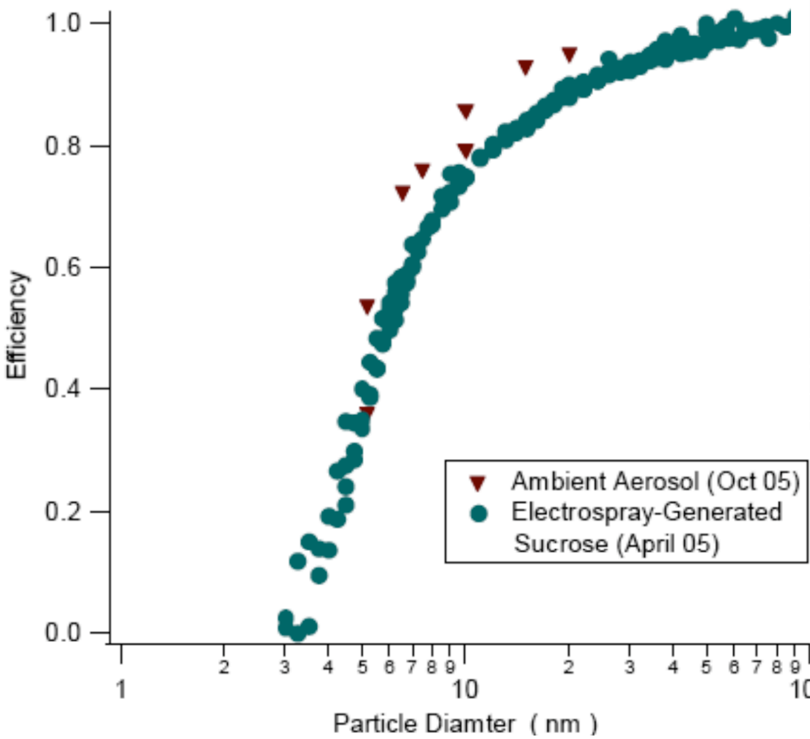
Field experimental scheme

- Observational monitoring
  - 3+ days per site with normal occupancy and use
  - Round-the-clock real-time monitoring
  - Aim for single period, but breaks at some sites
- Manipulation experiments
  - Building operation under researcher control
  - Air-exchange rate by tracer-gas decay
  - Particle penetration and persistence from outdoors
  - Characterize emissions and decay from representative indoor sources

Facilitating technology: WCPC

Particle number concentration (PN) is a good proxy for ultrafine particle concentration (UFP)





Conditioner T = 20°C

Growth tube T = 60 °C

Reference: SV Hering et al., *Aerosol Science & Technology* **39**, 659-672, 2005.

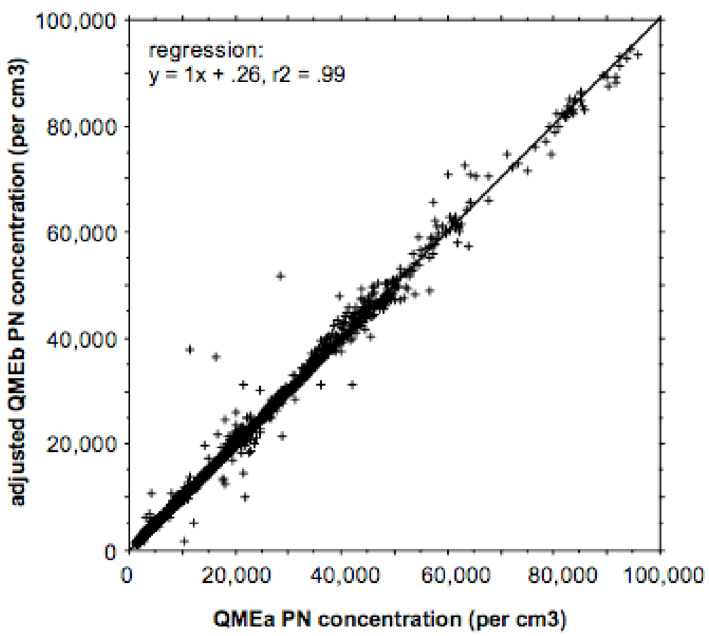
Real-time monitoring instruments

Parameter	Instrument	In1	In2	Out
PN (UFP) level	ME-WCPC (TSI 3781)	✓	✓	✓
CO_2 level	LI-COR 820	✓		
CO_2 level	TSI Q-Trak Plus 8554	✓		✓
CO level	TSI Q-Trak Plus 8554	✓		✓
Temperature	TSI Q-Trak Plus 8554	✓		✓
Relative humidity	TSI Q-Trak Plus 8554	✓		✓
Ozone level	2B Tech Model 202	✓		✓
Nitric oxide level	2B Tech Model 400	✓		✓

Monitoring: 1-min time resolution; 1.5 m height

QA/QC: Overview

- Ozone, NO, CO, CO_2 monitors calibrated ~ monthly against either reference instrument or standard gases.
- WCPC flow rates routinely checked in field
- Side-by-side monitoring conducted at each site.



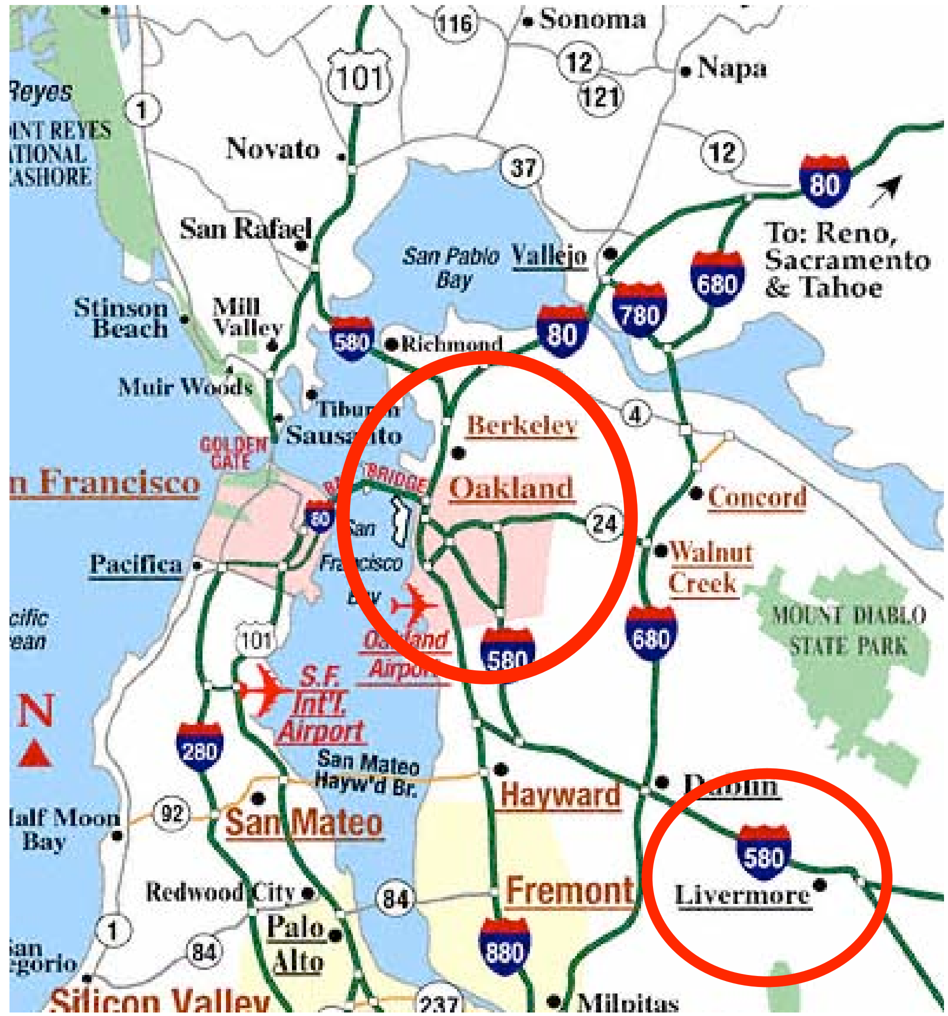
Sample WCPC side-by-side data (Indoor, H0)

Average WCPC side-by-side results: Slope of readings from instruments QMEb, QMEc, QMEd against reference instrument QMEa

Parameter	QMEb	QMEc	QMEd
Average	0.95	1.02	1.04
Std. dev.	0.10	0.14	0.14

Site selection: Houses

- Convenience sample
- All from East Bay area of Northern California
- Aggregate source-oriented selection criteria
- Aim for higher than average concentrations, but within normal range

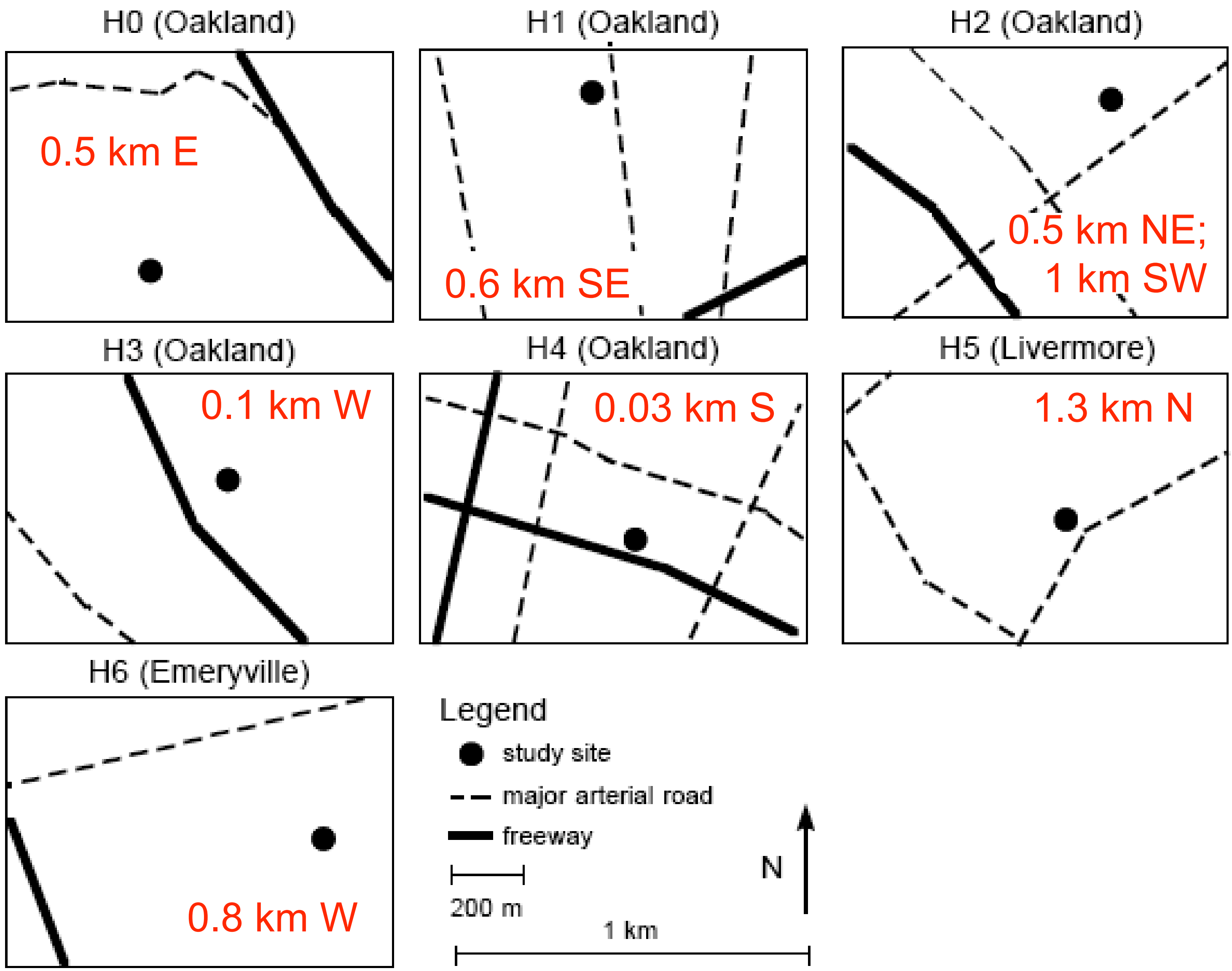


Some characteristics of house sites

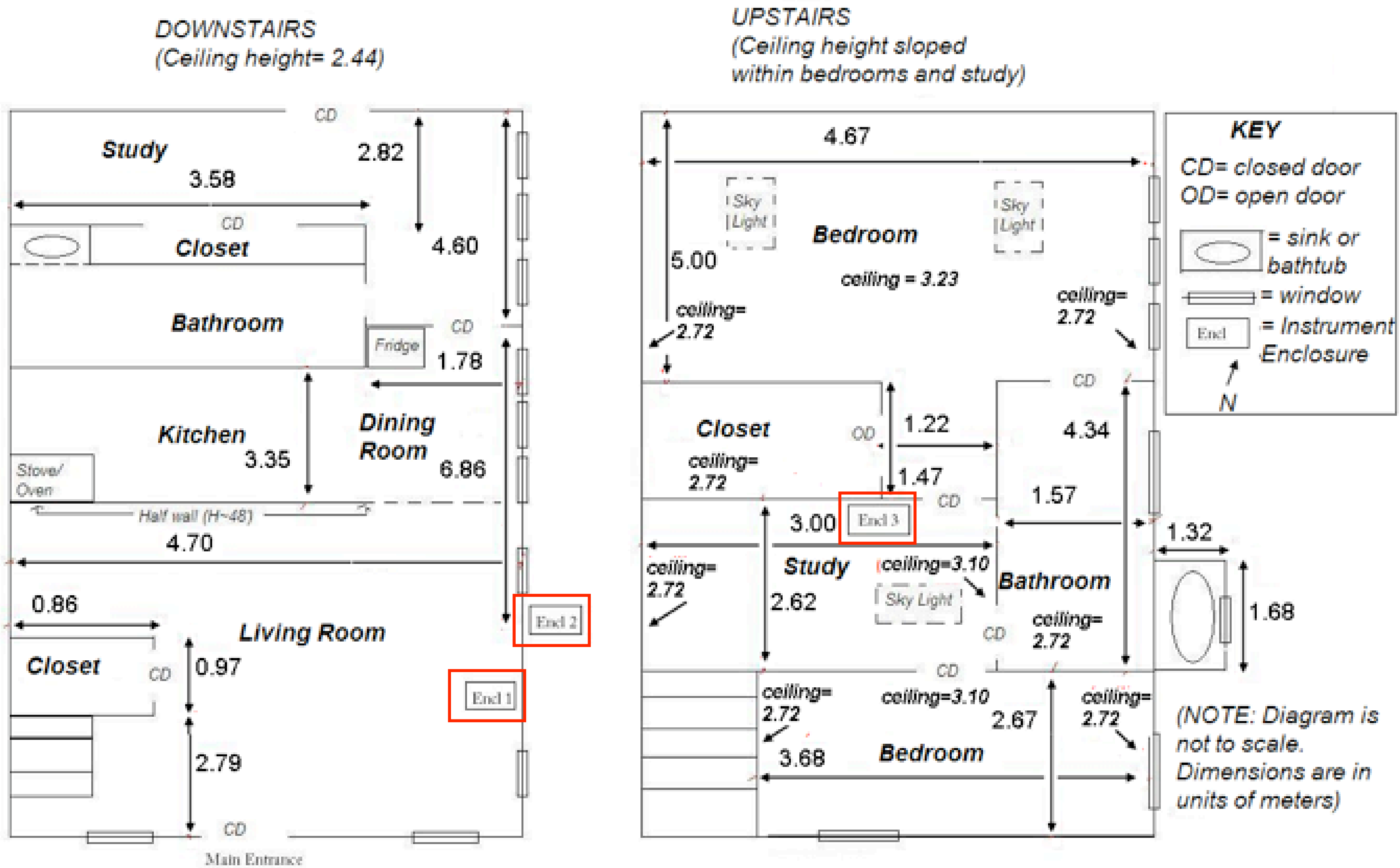
ID	City	Y built	V (m^3)	Residents [a]
H0	Oakland	1938	320	2 (M, F)
H1	Oakland	1910	315	4 (M, F, m, m)
H2	Oakland	1949	328	4 (M, F, m, m)
H3	Oakland	1928	200	3 (M, F, m)
H4	Oakland	1904	386	4 (M, F, m, m)
H5	Livermore	1993	420	1 (F)
H6	Emeryville	1996	314	3 (M, M, F)

[a] M — male adult, F — female adult, m — male child

House sites: Proximity to major roadways



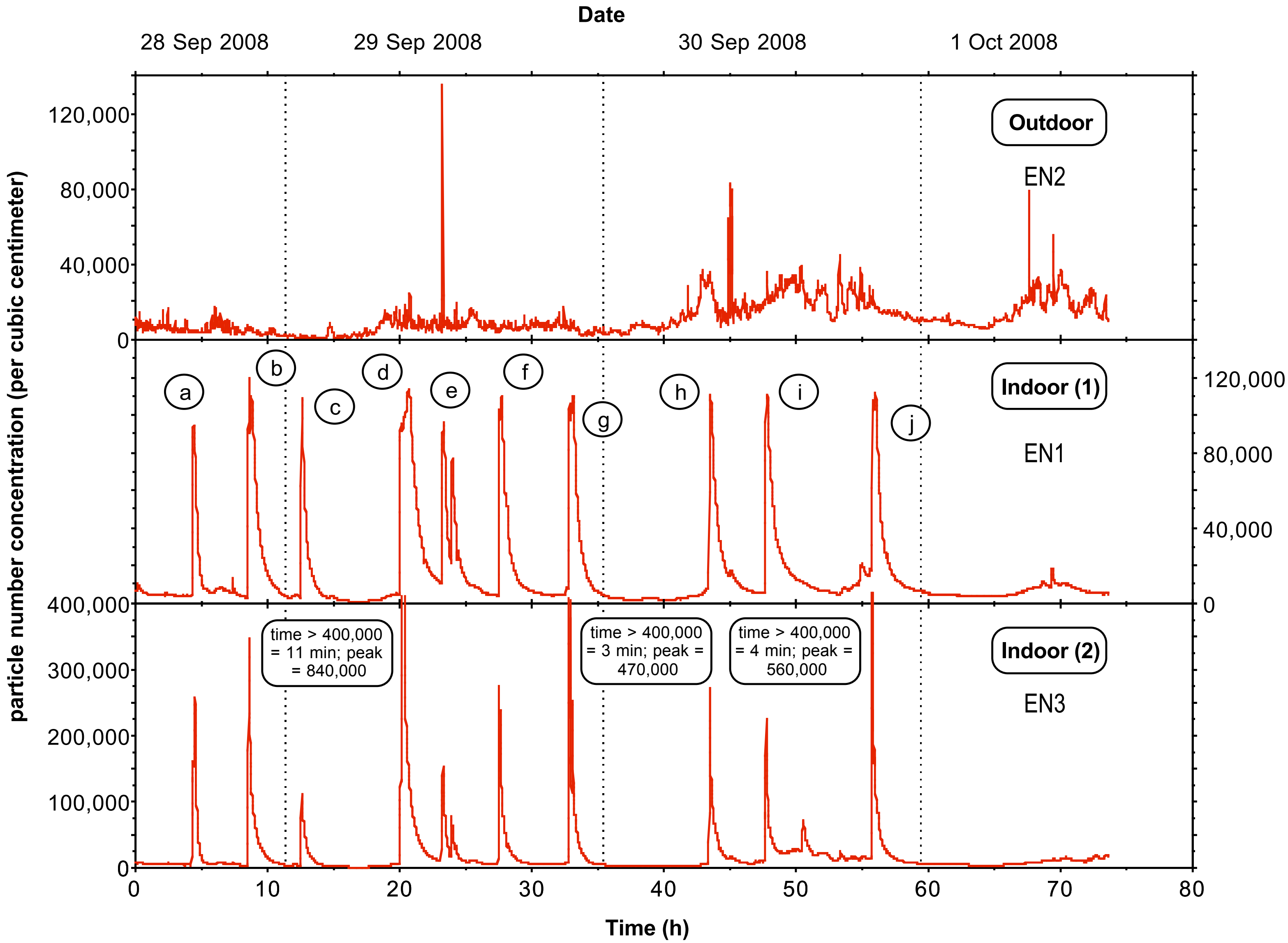
Some illustrative details: Site plan at H6



Some attributes of H6

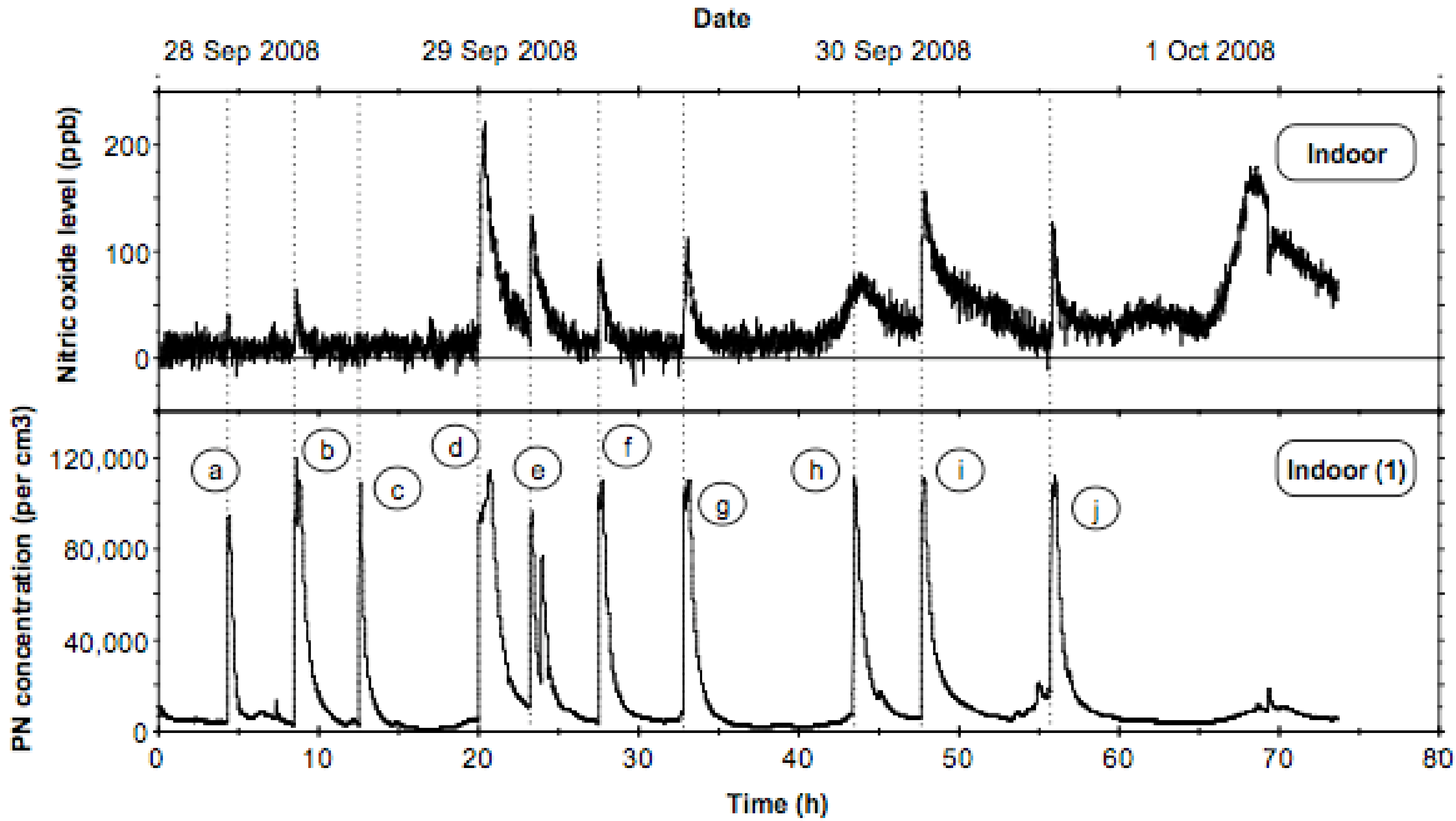
- Located in Emeryville, CA
- Built in 1996
- Occupants: 3 adults
- Pilotless gas range
- Used candles one time
- Air-exchange rate (3 measurements): 0.8-0.9 h^{-1}

PN concentration time series at H6



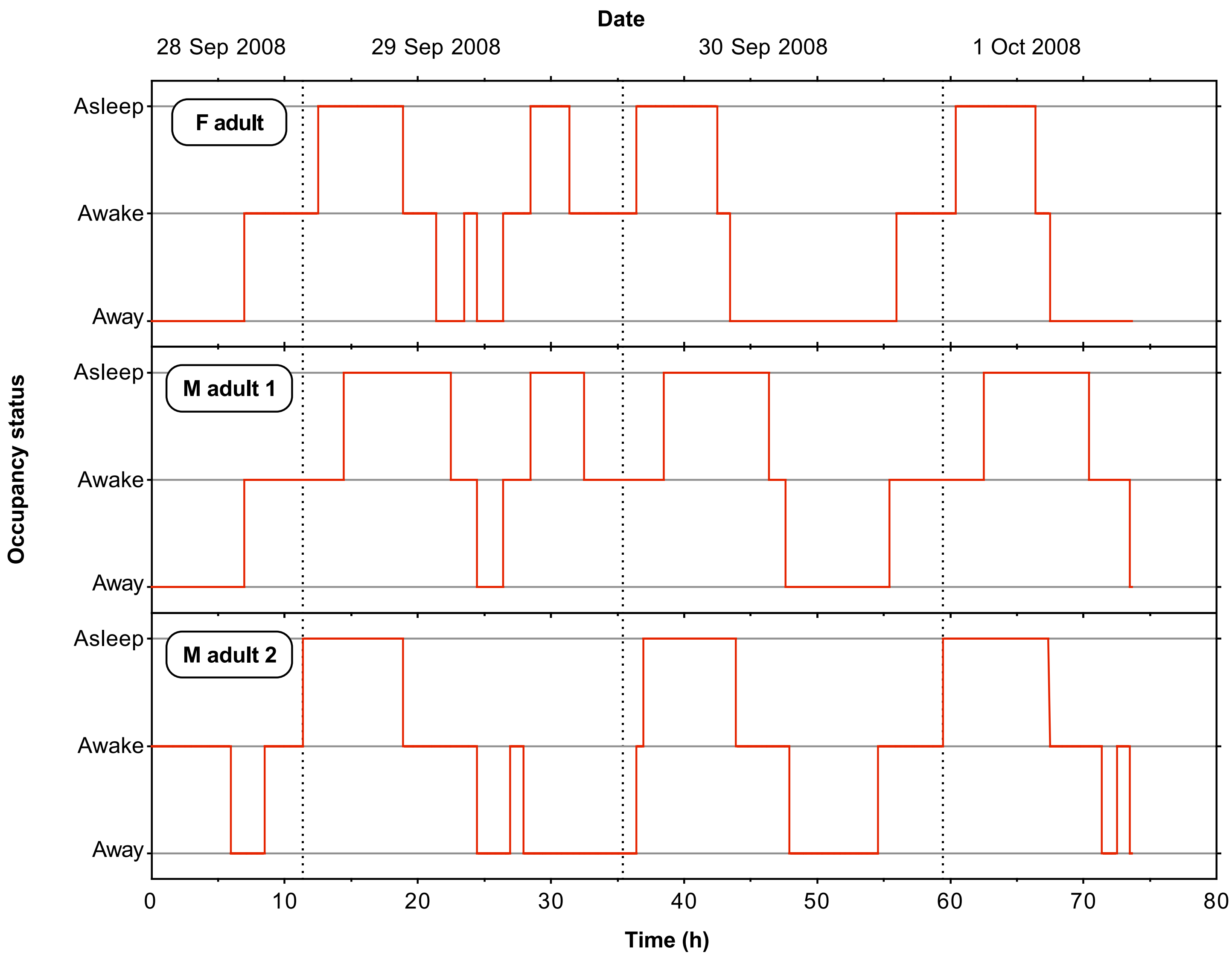
Cooking activities: (a), (b), (d), (e), (f), (g), (h), (i), (j); Use of candles: (c)

PN in relation to copollutant data: NO at H6



Cooking activities with gas range or oven: (a), (b), (d), (e), (f), (g), (i), (j); Candle use: (c); Toaster oven: (h)

Occupancy time-series data at H6



Indoor proportion of outdoor particles at H6

Table 3.49. Analysis of the indoor to outdoor particle concentration ratios at house site H6 for periods when the house is either unoccupied or all occupants are sleeping and there is no evidence of the influence of indoor sources on indoor PN levels.

Time (h)	**WS** ($m\ s^{-1}$)	**|ΔT|** (°C)	**PN_out** ($10^3\ cm^{-3}$)	**PN_in1** ($10^3\ cm^{-3}$)	**PN_in2** ($10^3\ cm^{-3}$)	f_1 (—)	f_2 (—)
14.5-18.9 [a]	1.8	7.8	3.6	2.0	1.8	0.54	0.50
25.3-26.4 [b]	3.7	3.5	10.3	8.3	8.9	0.81	0.87
38.5-42.4 [a]	0.9	9.4	8.9	2.7	2.5	0.30	0.28
51.5-54.6 [b]	2.8	5.0	21.7	7.1	16.5	0.33	0.74
62.5-66.4 [a]	1.0	10.2	8.3	3.9	4.0	0.47	0.48
Average	**1.7**	**7.9**	**9.9**	**4.0**	**5.7**	**0.44**	**0.51**

[a] Period when all three occupants were at home asleep and there was no evident influence of indoor sources on indoor PN levels.

[b] Period when the house was vacant and there was no evident influence of indoor sources on indoor PN levels.

Characterizing indoor PN sources at H6

Table 3.51. Analysis of indoor UFP sources at H6 from observational monitoring.

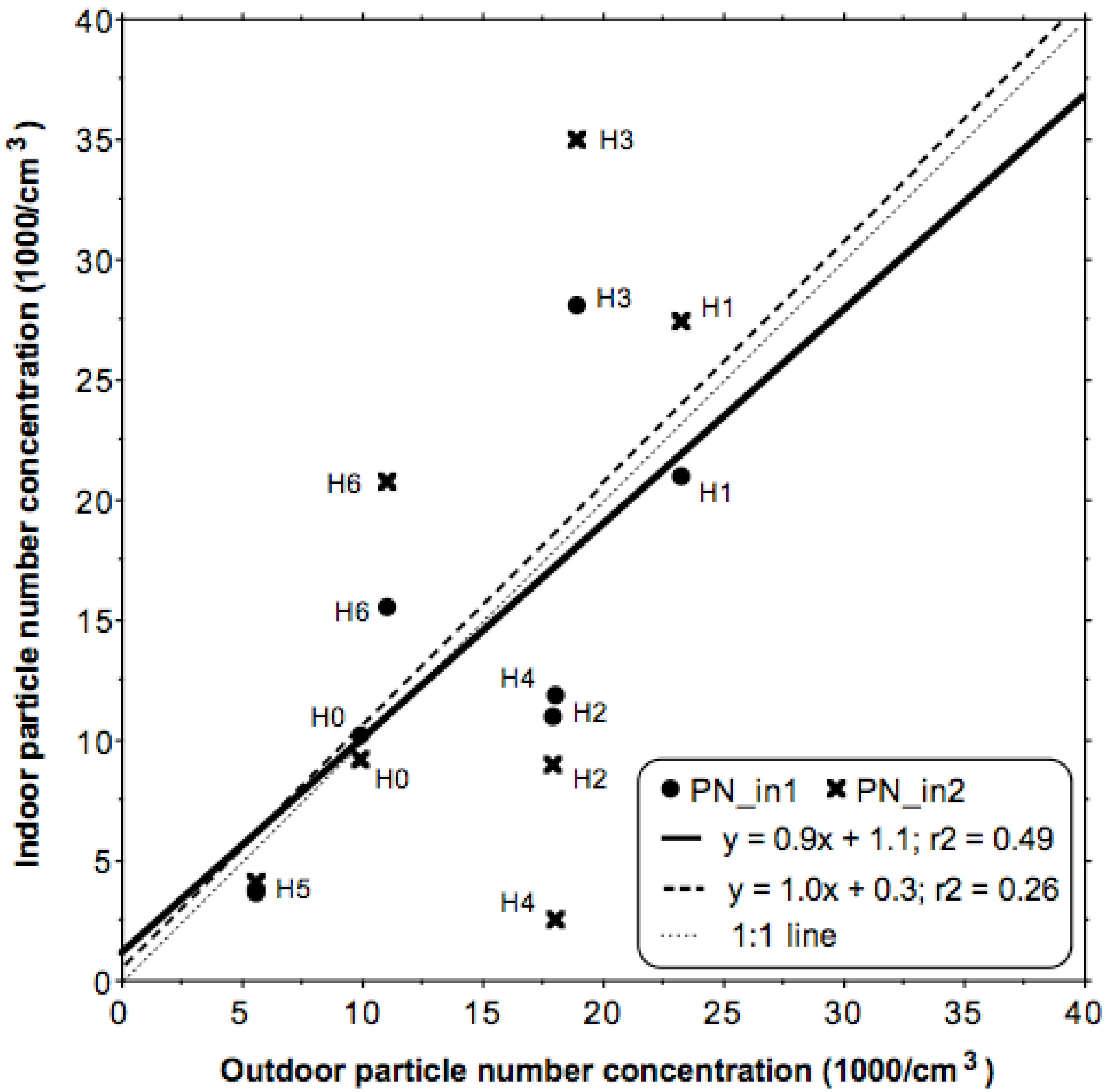
ID	Source activity	Time (h)	k+a (h^{-1})	σ/V (10^3 cm^{-3})	σ (10^{12})	(σ/V)/(k+a) (10^3 cm^{-3} h)
a	Stove & rice cooker	4.2-5.4	3.6	141	44	39
b	Stove (frying)	8.5-10.8	1.5	133	42	89
c	Candle	12.5-13.9	1.9	84	26	44
d	Stove (frying)	20.0-23.1	1.2	179	56	152
e1	Stove (water)	23.1-23.9	2.8	116	36	42
e2	Toaster oven	23.9-26.2	1.9	17	5	9
f	Stove (frying)	27.4-29.8	1.6	125	39	79
g	Stove (water) & microwave	32.8-34.8	1.8	146	46	81
h	Toaster oven	43.4-44.9	1.7	112	35	65
i	Stove (water & frying)	47.6-50.3	1.5	110	35	72
j	Stove & GF grill	55.6-59.1	1.5	127	40	83

Exposure & apportionment at H6

Table 3.53. Exposure analysis for resident of house site H6 during observational monitoring

Parameter	**R1 (F)**	**R2 (M)**	**R3 (M)**
Occupancy status			
Time at home, awake (h)	22.5	28.8	29.8
Time at home, asleep (h)	21.5	28.0	22.5
Time away from home (h)	29.7	16.9	21.4
Exposure duration (d)	3.1	3.1	3.1
Average exposure concentrations and exposures			
Average concentration (PN_in1), indoor awake (10^3 cm^{-3})	24.7	19.4	23.1
Average concentration (PN_in2), indoor asleep (10^3 cm^{-3})	5.3	17.4	7.3
Cumulative exposure (10^3 cm^{-3} h)	669	1045	854
Cumulative exposure rate (10^3 cm^{-3} h d^{-1})	218	341	278
Indoor exposure attributable to particles of outdoor origin			
Cumulative contribution to exposure (10^3 cm^{-3} h)	155	270	251
Percentage attributable to particles of outdoor origin	23%	26%	29%
Exposure attributable to indoor source peaks (10^3 cm^{-3} h)			
Peak a — Stove and rice cooker	0	0	39
Peak b — Stove (frying)	89	89	89
Peak c — Candle	38	44	38
Peak d — Stove (frying)	119	281	152
Peak e — Stove (water) and toaster oven	37	64	64
Peak f — Stove (frying)	76	76	44
Peak g — Stove (water) and microwave	81	81	0
Peak h — Toaster oven	1	70	73
Peak i — Stove (water & frying)	0	3	28
Peak j — Stove and grill	64	83	83
Cumulative exposure attributable to episodic indoor sources	506	791	611
Percentage attributable to quantified episodic indoor sources	76%	76%	72%
Indoor exposure of unknown origin			
Cumulative exposure (10^3 cm^{-3} h)	8	-16	-9
Percentage of unknown origin	1%	-2%	-1%

All houses: Relationship of PN in to PN out



Overall averages:

In1: 14.5 ± 8.0

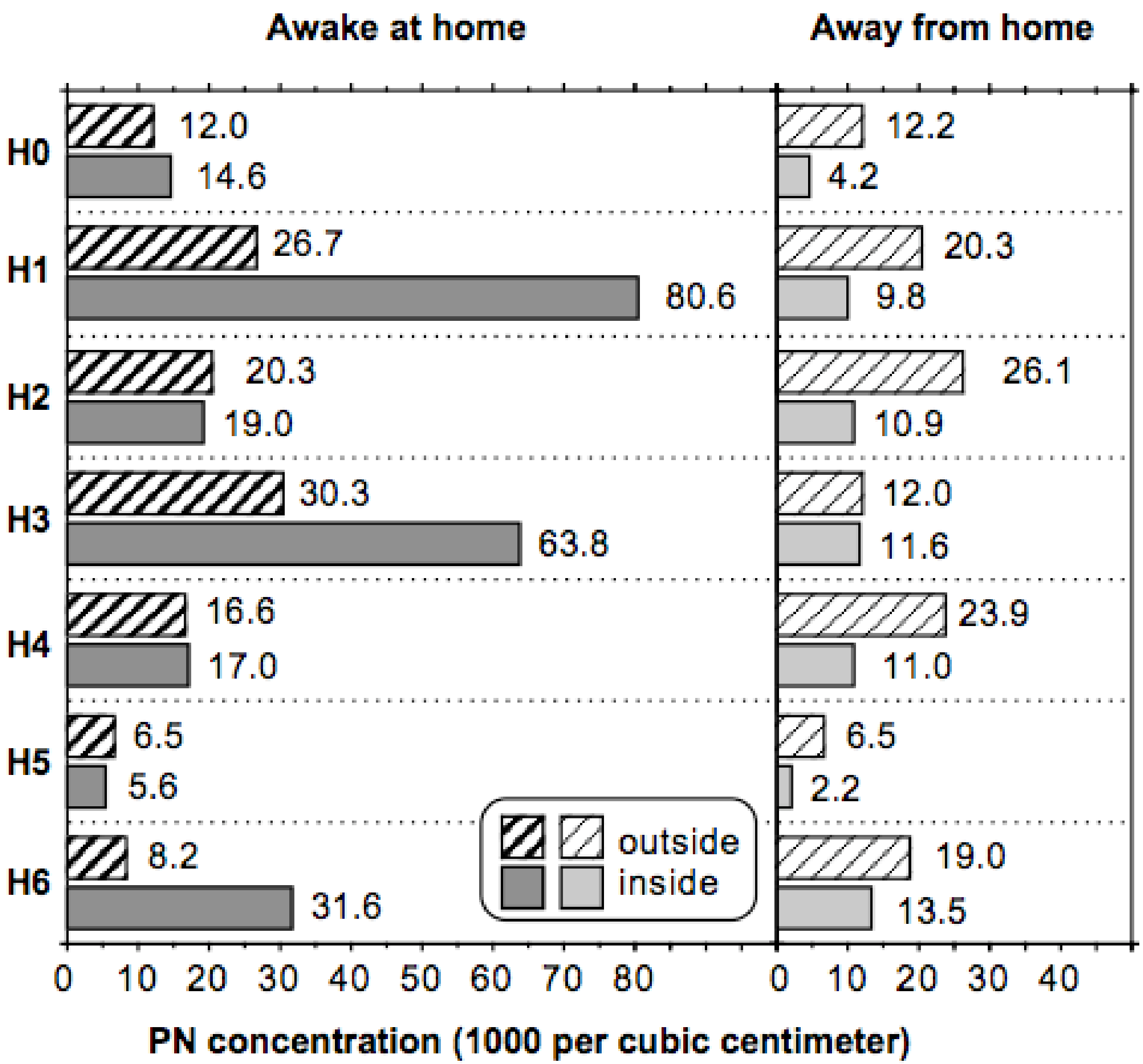
In2: 15.4 ± 12.4

Out: 14.9 ± 6.2

(units: 10^3 per cm^3)

Averages are similar; correlations are not very good.

Indoor PN: Higher when people are awake



Averages

awake at home:
outside — 17.2
inside (In1) — 33.2
inside (In2) — 35.6

asleep at home:
outside — 8.9
inside (In1) — 5.0
inside (In2) — 5.5

away from home:
outside — 17.1
inside (In1) — 9.0
inside (In2) — 9.7

All in units of 10^3 cm^{-3}

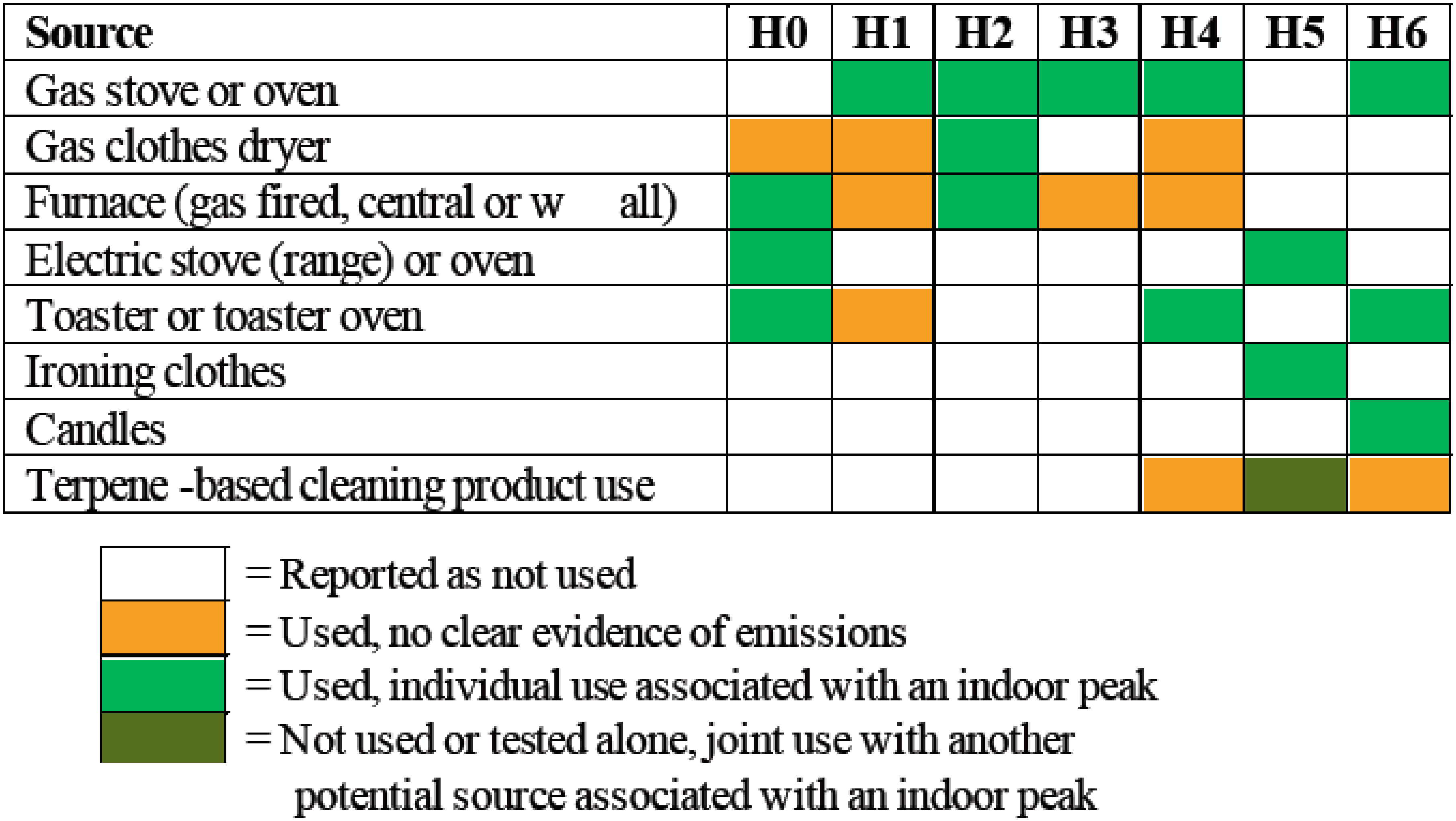
Indoor proportion of outdoor particles (*f*)

- Goal: Determine average indoor concentration of UFP only attributable to average outdoor concentrations.

Site	Dur.	f_1	f_2	Note
H0	30 h	0.36	0.37	
H1	30 h	0.11	—	Time-weighted average of conditions with bathroom window open (f_1 = 0.25); windows closed and air handler off (f_1 = 0.16); and windows closed with air on (f_1 = 0.074). Model fit developed using integral material balance approach accounting for emissions from pilot lights.
H2	28 h	0.51	—	
H3	63 h	0.45	—	Based on regression analysis of indoor vs. outdoor concentrations for full monitoring period after first removing from record times when indoor sources had an evident influence on PN levels.
H4	22 h	0.47	0.11	Upstairs (f_2) floor has continuously operating air cleaner.
H5	29 h	0.29	0.49	Activity-weighted average of AC off (f_1 = 0.43) and AC on (f_1 = 0.11) yields f_1 value. The value for f_2 is based on 8.5 h with AC off.
H6	16 h	0.44	0.51	Includes periods when all occupants are asleep (12 h) in addition to period when house is vacant and there is no evident influence of indoor sources in indoor PN levels (4 h).

- Results summary (f_1): avg ± stdev = 0.38 ± 0.14; median = 0.44

Qualitative summary of indoor sources

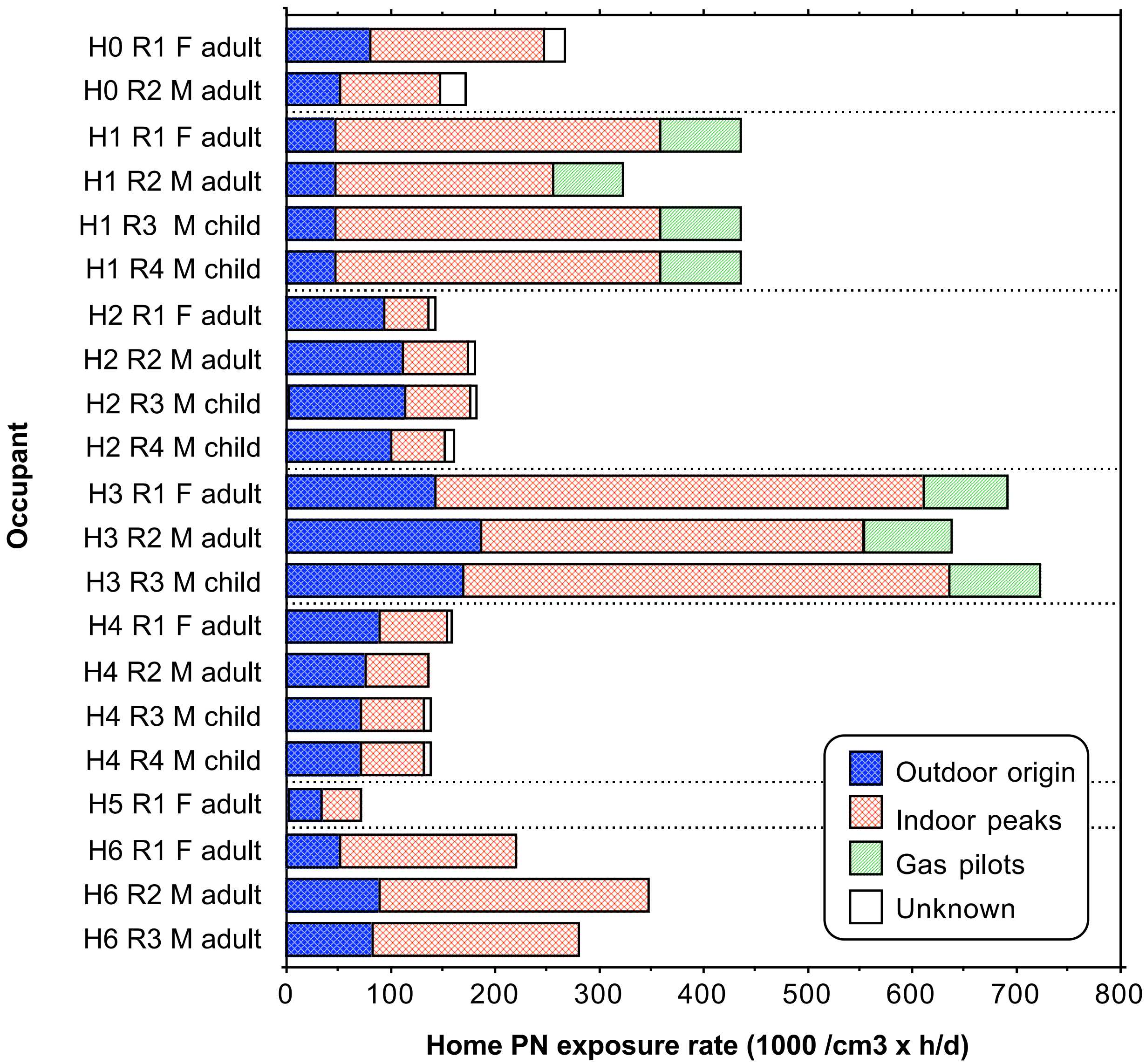


Episodic emissions characterization

- Overall summary: 59 peak events ~ 2.4 events per day
- For peaks associated with distinct activities:
  - — Characterized PN emissions (σ) for 40 events
  - — Characterized decay constant (k+a) for 38 events

Source	***k* + *a*, GM (GSD; N)**	**σ, GM (GSD; N)**
Gas stove	1.8 h^{-1} (1.4; 20)	38 × 10^{12} particles (2.1; 19)
Furnace, central	1.6 h^{-1} (1.5; 2)	41 × 10^{12} particles (1.1; 2)
Candle	1.9 h^{-1} (—; 1)	26 × 10^{12} particles (—; 1)
Toaster oven	1.7 h^{-1} (1.2; 4)	9 × 10^{12} particles (2.8; 4)
Electric stove	1.1 h^{-1} (1.3; 5)	10 × 10^{12} particles (2.1; 4)
Furnace, wall	1.3 h^{-1} (1.7; 3)	3.1 × 10^{12} particles (2.7; 7)
Clothes dryer	2.2 h^{-1} (—; 1)	2.2 × 10^{12} particles (—; 1)
Steam iron	1.5 h^{-1} (1.2; 2)	1.9 × 10^{12} particles (1.4; 2)

PN exposures and apportionment



Averages (21 people)

Total exposure: 298 ± 195
Outdoor origin: 86 ± 42
Indoor peaks: 182 ± 144
Gas pilots: 23 ± 34
Unknown: 5 ± 6

Units: 10^3 cm^{-3} h/d

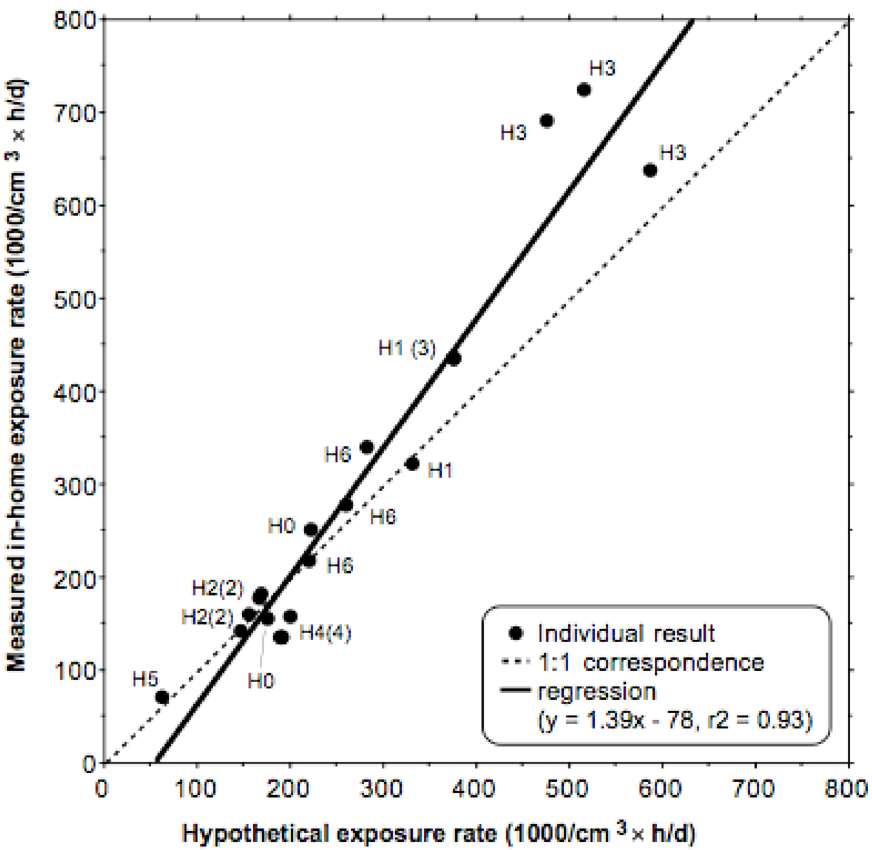
Proportions (average)

Total exposure: 100%
Outdoor origin: 29%
Indoor peaks: 61%
Gas pilots: 8%
Unknown: 2%

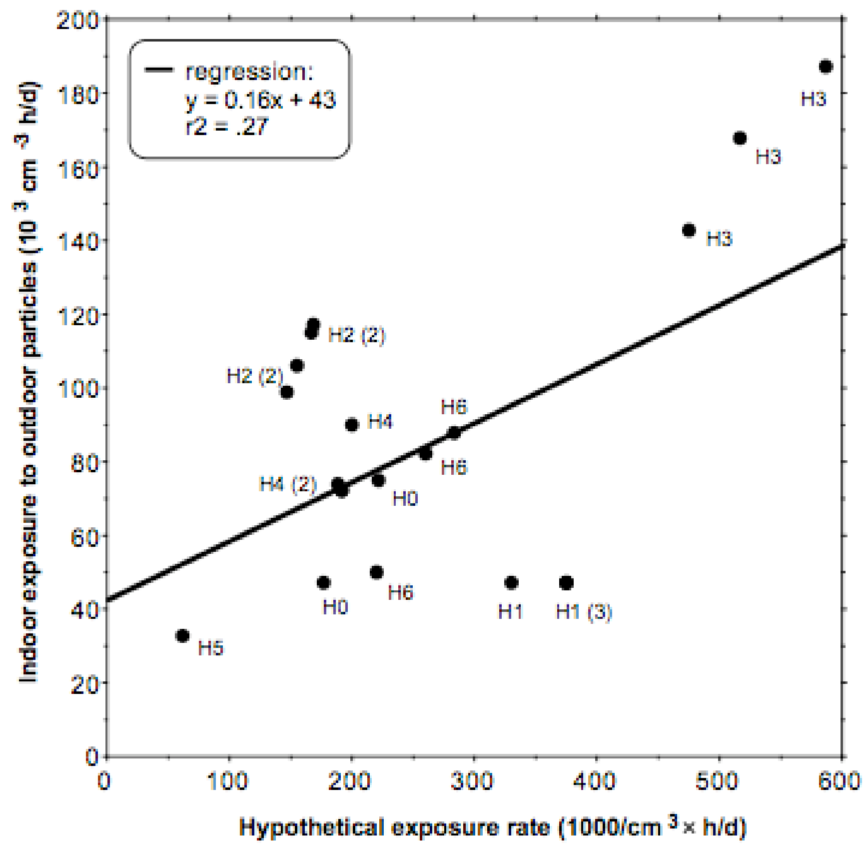
Units: 10^3 cm^{-3} h/d

Exposures measured vs. hypothetical

Total residential PN exposure



Residential exposure to outdoor PN



Hypothetical exposure rate is product of measured outdoor PN level times the average daily duration of occupancy of the individual.

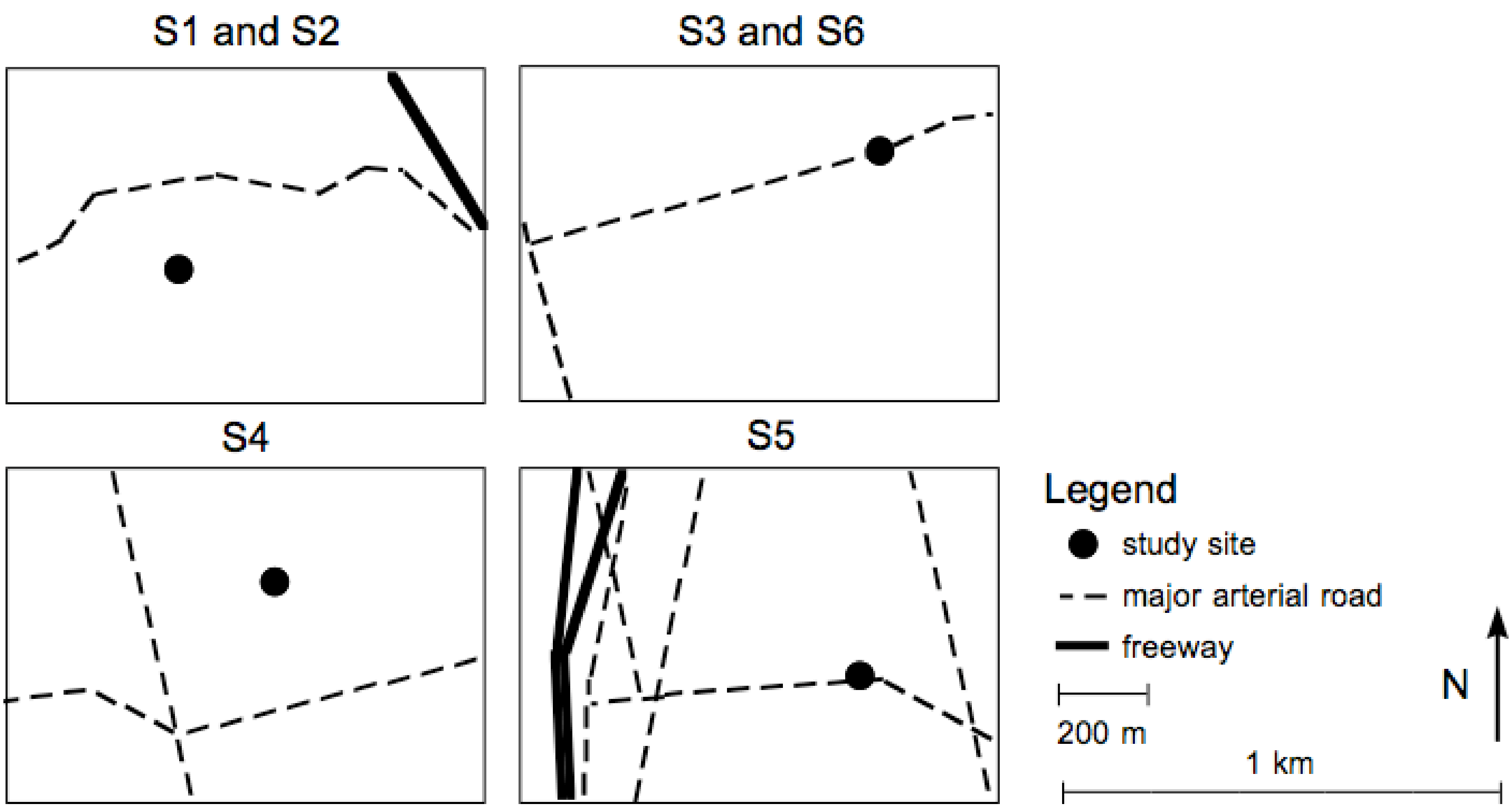
Site selection: Schools

- Convenience sample
- Elementary schools in the urban portion of the East Bay of Northern California

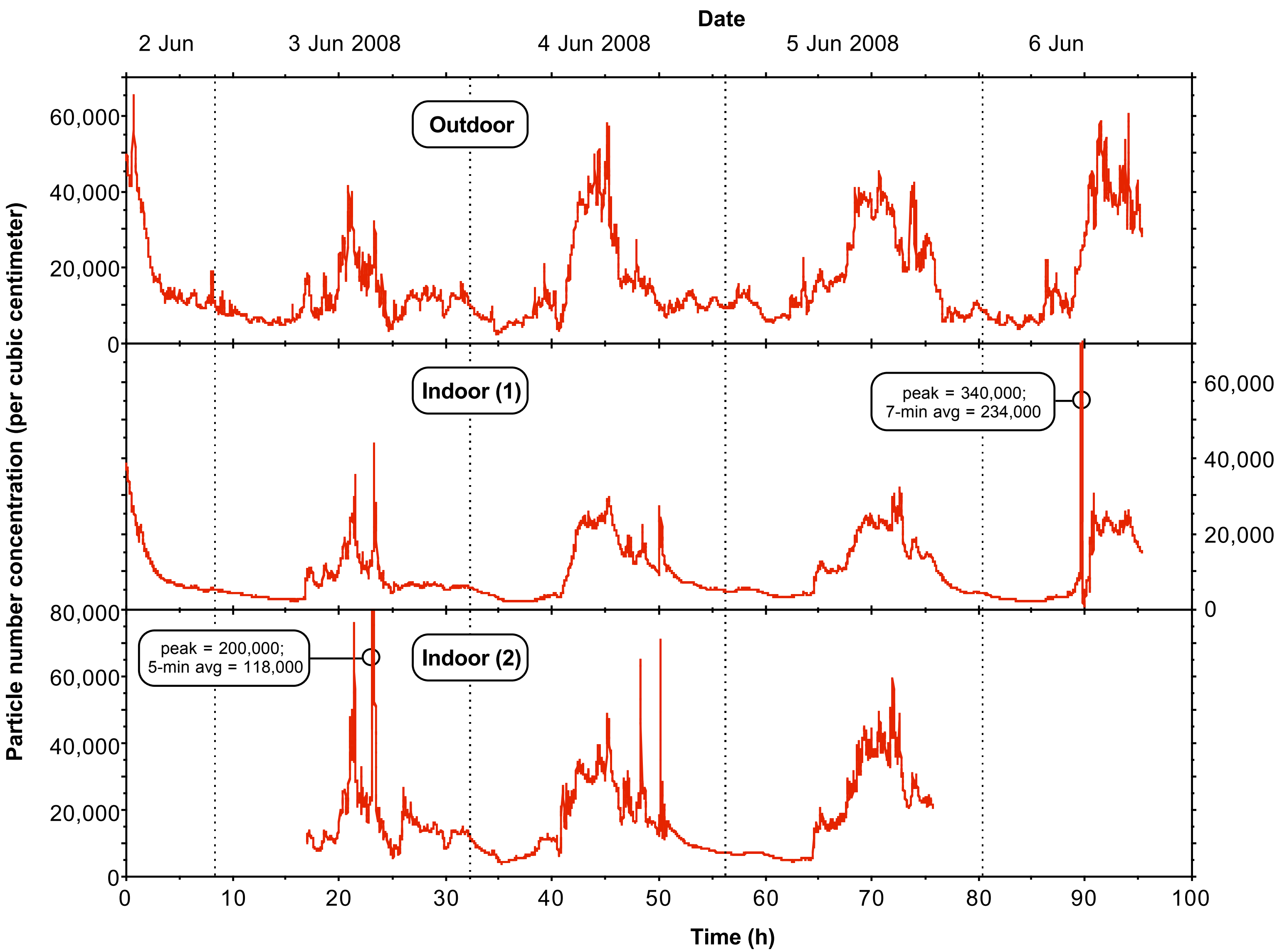
Some characteristics of school sites

ID	Date	Description
S1	June 2008	3rd and 4th grade students; older classroom; natural ventilation only using doors/windows; V ~ 290 m^3
S2	Oct. 2008	1st & 2nd grade students; new classroom with mechanical air handling & particle filter; V ~ 240 m^3
S3	Oct. 2008	2nd grade students; constructed in 1980s; mechanically ventilated; V ~ 205 m^3
S4	Nov. 2008	5th grade students; building > 100 y old; natural ventilation only; V ~ 230 m^3
S5	Nov. 2008	4th grade students; constructed in 1970s; mechanically ventilated classroom; V ~ 260 m^3
S6	Dec. 2008	2nd grade students; constructed in 1980s; equipped with wall mounted ventilation; V ~ 300 m^3

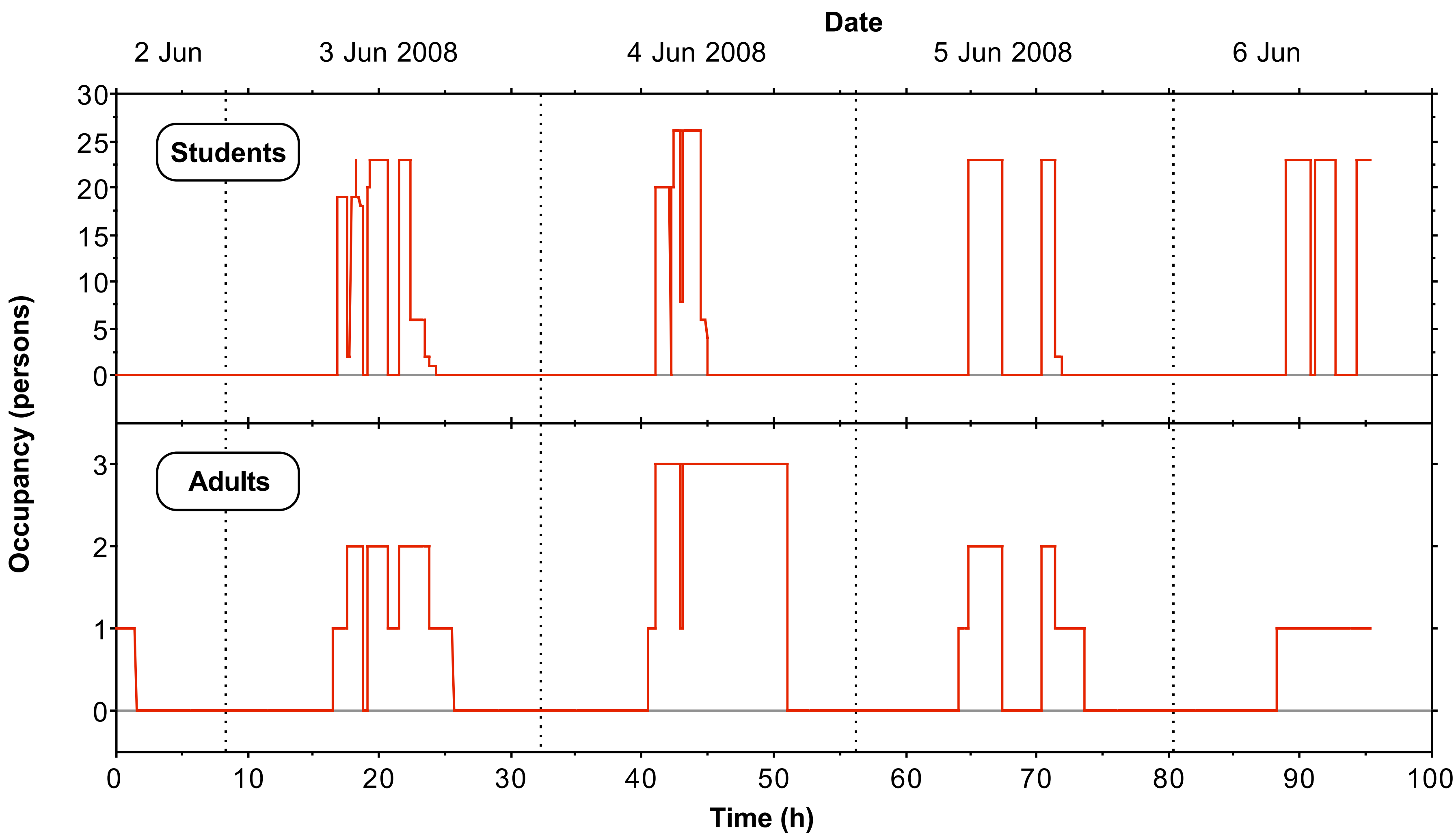
School sites: Proximity to major roadways



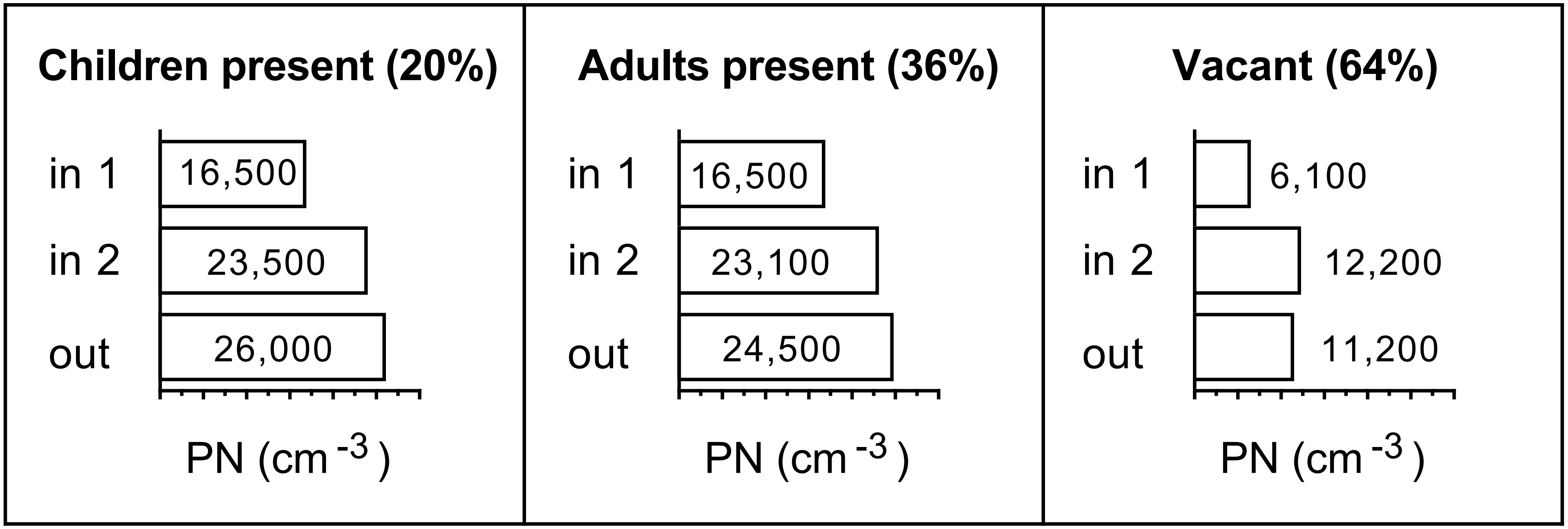
Sample data: PN concentration vs. time at S1



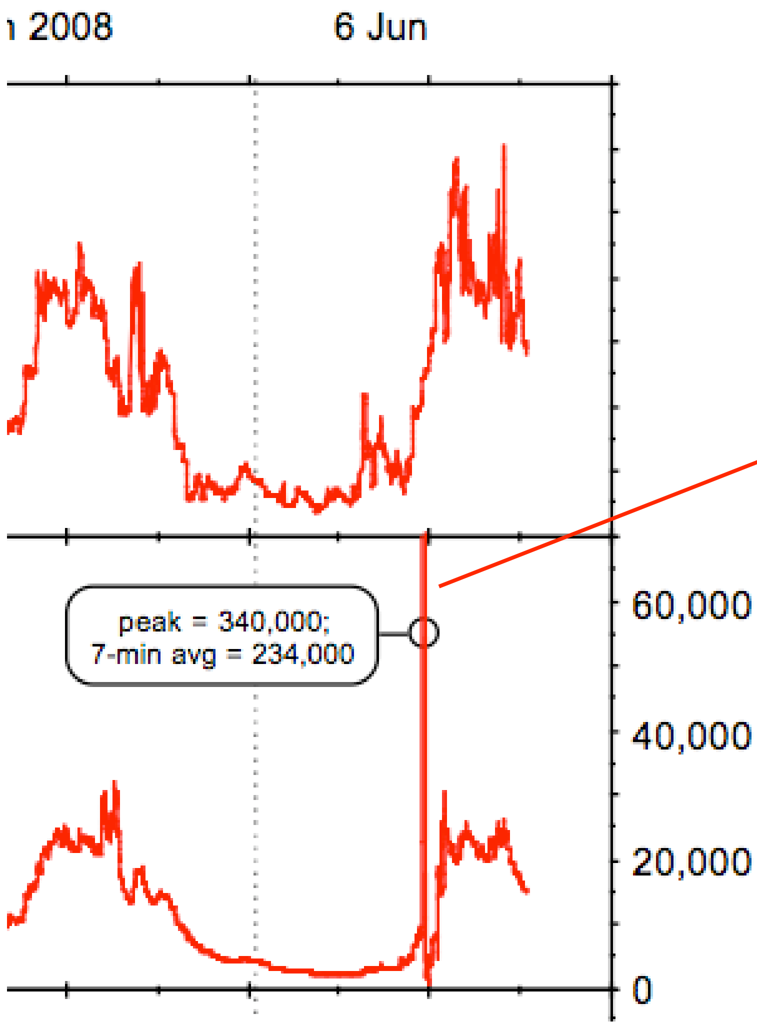
S1: Occupancy time-series data

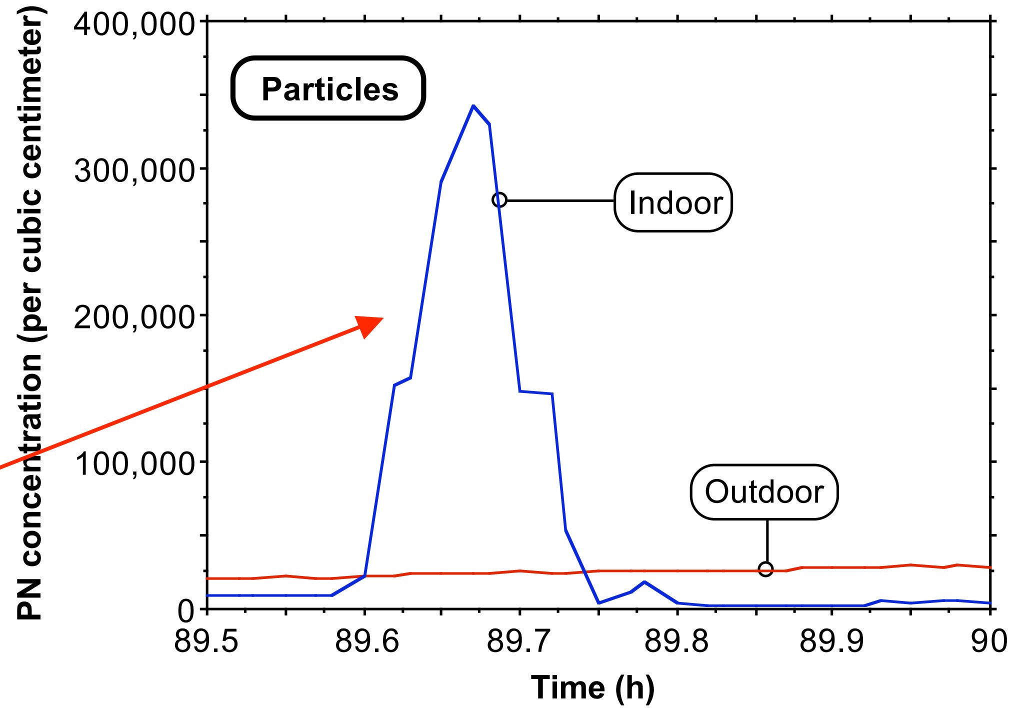


S1: Time-average PN levels with occupancy



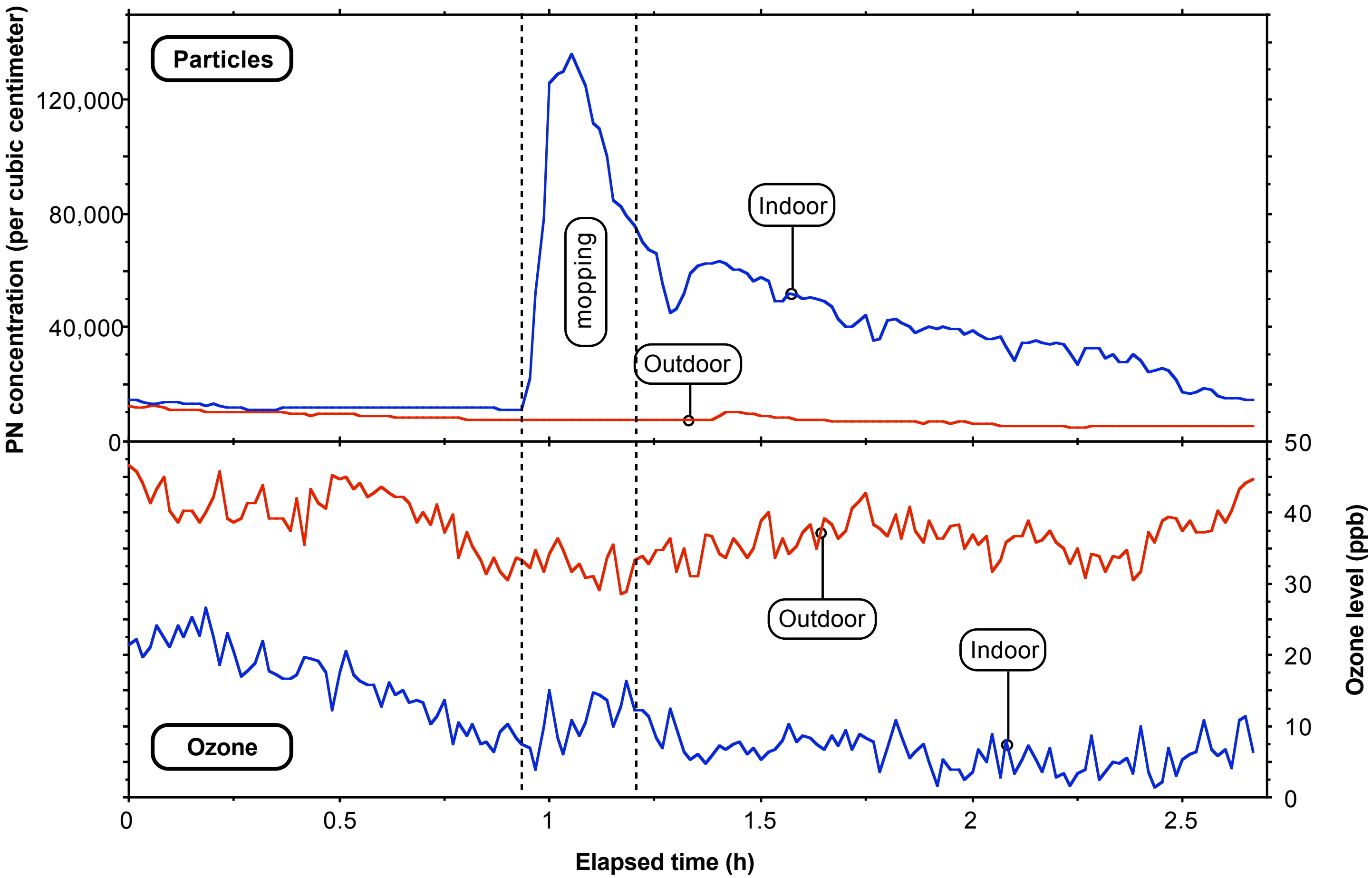
S1: Source peak from cooking pancakes





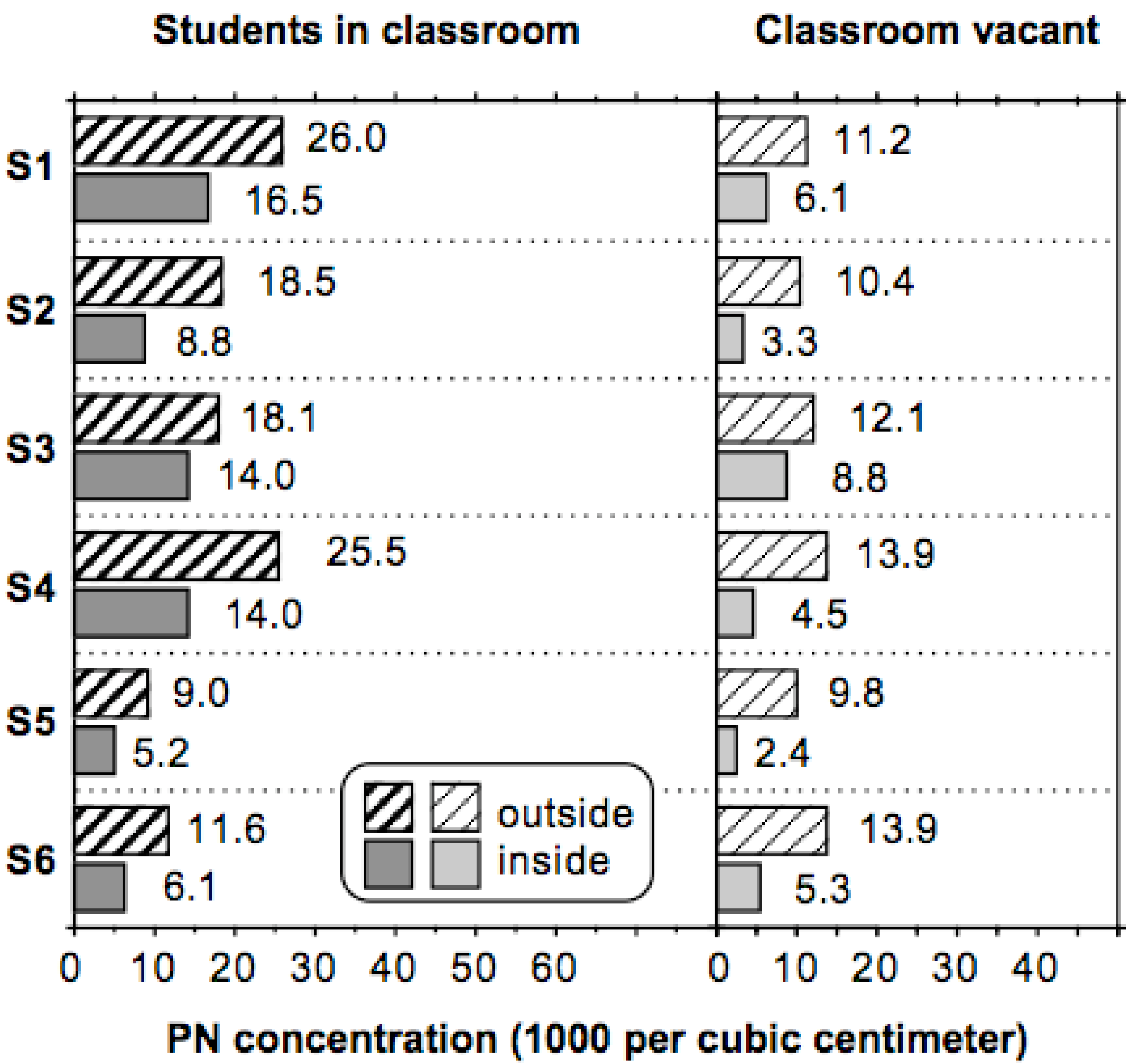
This brief peak contributed 10% to students' exposure and 5% to teacher's exposure for the three school days monitored.

S1: PN peak from mopping (manipulation)



Explanation: Ozone reacts with terpenes in pine oil to form condensable species that first nucleate to form new particles and then condense to cause particle growth.

Summary for classrooms: PN levels



Averages

occupied:
outside — 18.1 ± 7.0
inside — 10.8 ± 4.7

vacant:
outside — 11.9 ± 1.7
inside — 5.1 ± 2.3

All in units of 10^3 cm^{-3}

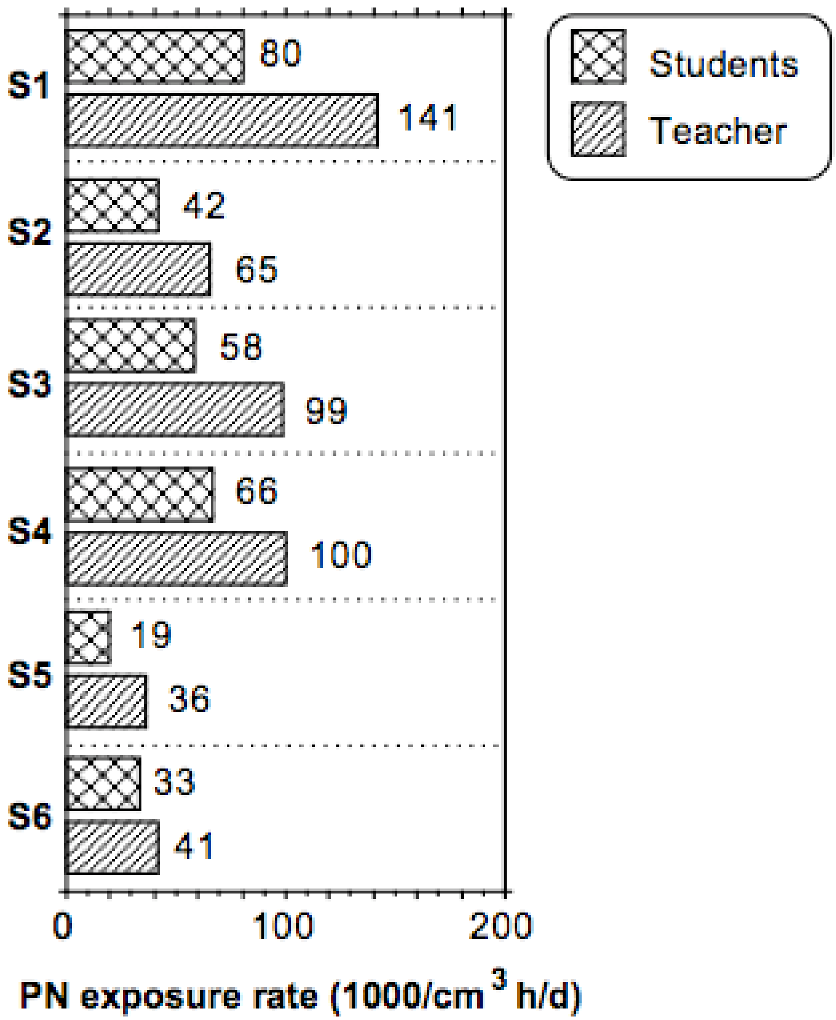
Indoor proportion of outdoor particles (*f*)

- Air-exchange rate (AER) has important influence.

	Doors closed; air off			Door(s) open and/or air on		
Site	**Time (%)**	**AER (h^{-1})**	**f_1 (—)**	**Time (%)**	**AER (h^{-1})**	**f_1 (—)**
S1	3%	0.5	0.39	96%	2.2	0.59
S2	35%	0.4	0.16	53%	3.3	0.54
S3	0%	—	—	100%	4.6	0.76
S4	25%	0.3	0.46	68%	3.9	0.59
S5	0%	—	—	100%	1.9	0.51
S6	76%	0.6	0.51	17%	4.0	0.60
Avg.	**23%**	**0.45**	**0.38**	**72%**	**3.1**	**0.60**

- Results summary:
  closed state $f_1 = 0.38 \pm 0.15$
  open state $f_1 = 0.60 \pm 0.09$

Summary for classrooms: PN exposure rates

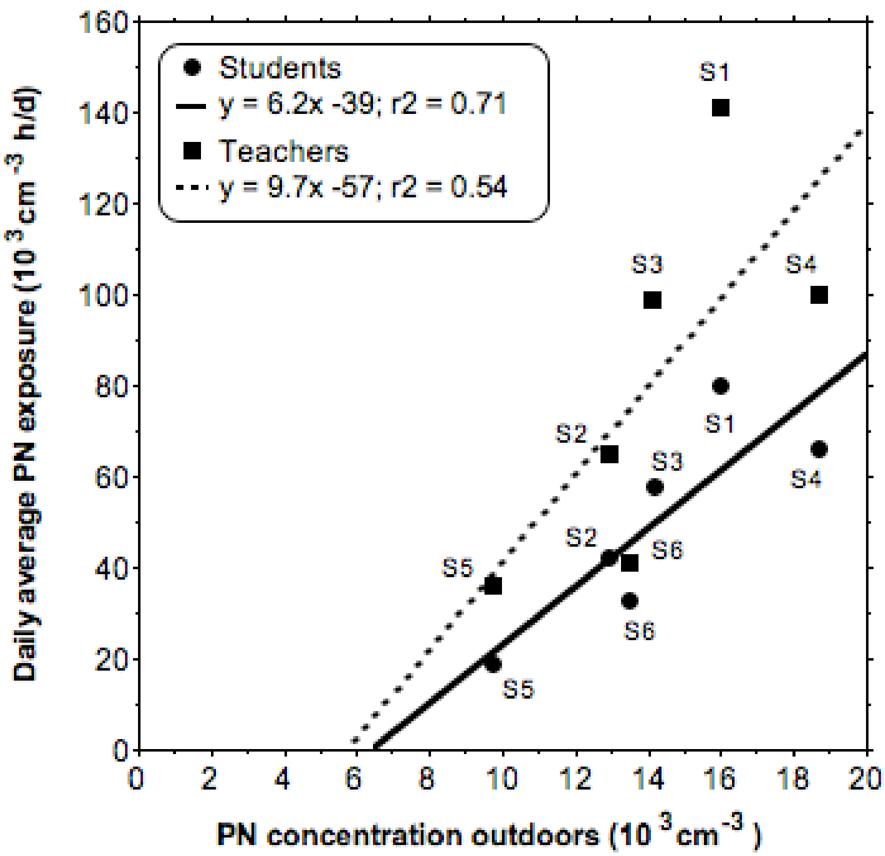


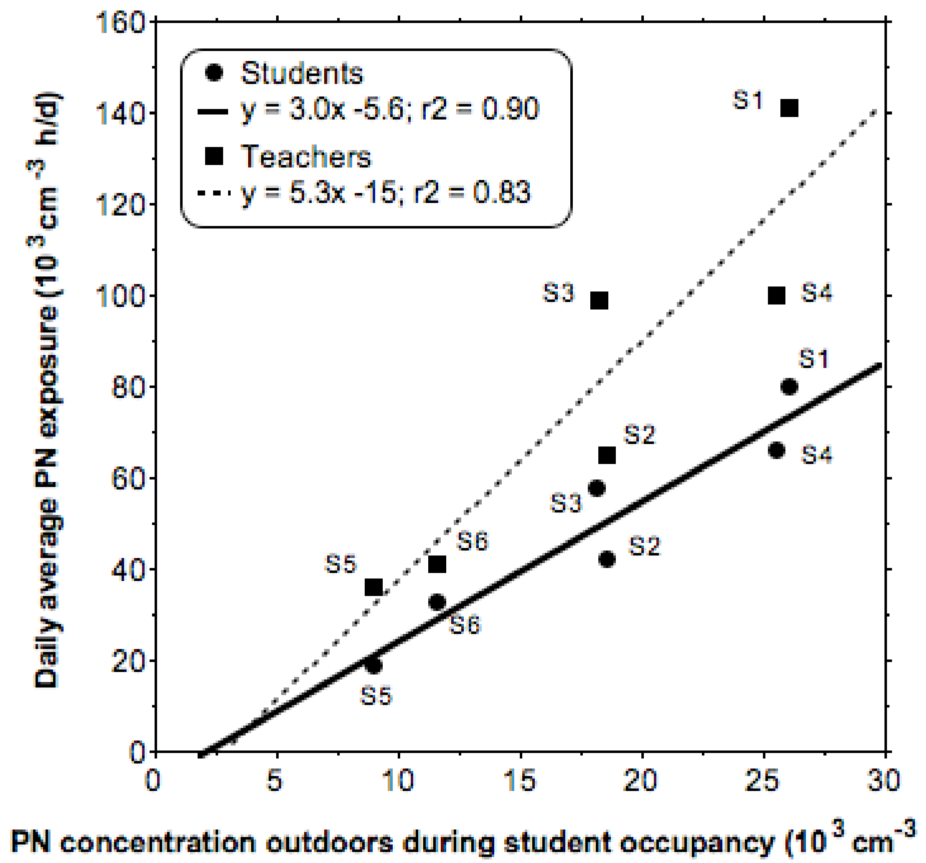
Average ± standard deviation

Students: 50 ± 22
Teachers: 80 ± 40

Units: 10^3 cm^{-3} h/d

Exposures related to outdoor concentrations

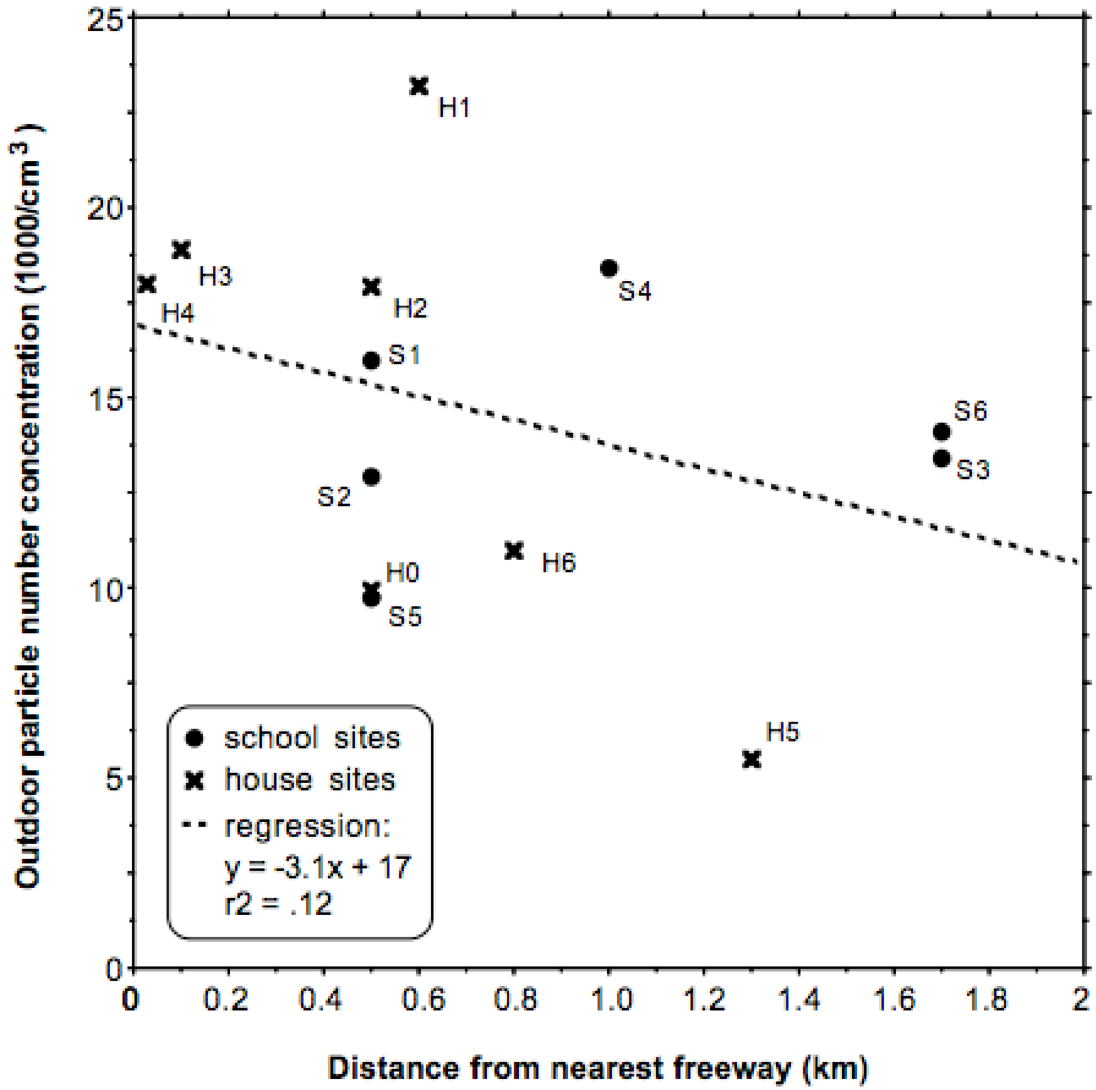




- Ambient PN levels *during occupancy* are predictive of average PN exposures.

Outdoor PN level vs. proximity to freeway

Distance to nearest freeway was not strongly correlated with outdoor average PN levels on days sampled.



UFP in classrooms and houses: Key findings

1. PN levels in classrooms and in houses are much higher when occupied than when vacant.
2. Indoor emission sources are important in houses, but not in classrooms.
3. Daily average PN exposures per person are much higher in houses (~ 300×10^3 cm^{-3} h/d) than in schools (students ~ 50×10^3 cm^{-3} h/d; teachers ~ 80×10^3 cm^{-3} h/d).
4. Indoor proportion of outdoor particles tends to be higher in classrooms (0.57 ± 0.10) than in houses (0.38 ± 0.14).

Caveats: Small sample of buildings, not statistically representative, few days monitored, one area of California.

Broad extrapolation not warranted!

Recommendations

1. Conduct additional monitoring studies of ultrafine particles in classrooms and houses.
2. Study effects of spatial and temporal variability on pollutant exposure.
3. Systematically investigate near-field effects of motor vehicle emissions on indoor UFP levels.
4. Study emissions from and exposure to UFP from cooking activities.